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Research Article

# Multi-objective Optimization of Blood Supply Network Using the Meta-Heuristic Algorithms

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**Abstract**

Management of blood product consumption is a complex and important issue in health systems. Limited blood supply, corruption, special conditions for storage of blood products, and high costs due to losses and shortage of blood in medical centers are among the factors affecting the problem. In this study, all three levels of donors, blood collection centers, and customers (hospitals) are considered for modeling the blood supply network in the form of a multi-objective model. Three objectives of the proposed model are: (a) minimizing total costs, (b) minimizing total delivery time of blood units, and (c) minimizing the maximum unmet demand of hospitals in each period. Next, the model used two multi-objective optimization algorithms namely NSGAII and MOPSO algorithms for solving 30 sample problems in different dimensions (small, medium, and large). After solving the sample problems, the efficiency of the two algorithms were compared with each other. According to the results, for the cost objective function and each of its components separately, it can be seen that the values resulted from the NSGA-II algorithm were less than the MOPSO. Finally, a real word data set from the Tehran blood center was used to evaluate the validity of the proposed model.

***Keywords***: Multi-objective optimization; Blood; Supply chain; MOPSO; NSGA II

## 1. Introduction

Health expenditures are increased dramatically during the last 50 years. For example, in the united states, 5% of the gross domestic product (GDP) in 1960, 14.1% of GDP by the year 2001, and 17.9% of GDP by the year of 2010 accounts for healthcare spending raised to 20% by the year 2021. In underdeveloped countries, this growth rate is also ascending. In Iran, for example, health services accounted for 4.87% by the year 2000, 6.69% GDP of by the year 2010, and 8.46% by the year 2018 and the trend is still increasing for many reasons such as aging population, increasing the costs of medicine, new medical technologies and costly procedures of healthcare services (Zahiri et al., 2018; Tavakkol et al., 2023).

According to reports, about 10% of Iran's population died or was injured between 1999 to 2018, which placed in the 7th rank among the ten accident-prone countries (Habibi-Kouchaksaraei et al., 2018). This increased blood demand due to the increase in blood consumption mainly for trauma and surgeries (Spahn, 2018). As a prediction, blood demand increases at the rate of 4–5% each year. While just 5% of the population donates blood which results in a blood shortage in blood centers and hospitals (Pirabán et al., 2019; Rajendran and Ravindran, 2019).

Blood shortage has an irrecoverable cost for society because it increases the fatality rate (Habibi-Kouchaksaraei et al., 2018). Moreover, blood wastage is also irrecoverable because human blood is a vital and rare resource. It is extracted from the human body and currently, there is no other product or superseded chemical process that can be replaced with human blood. Moreover, blood is a degradable product, which itself increases the complexity of the problem. In addition, from all donated blood units, only a small amount is usable, and there should be a certain time interval between two blood donations by an individual. Thus, in the required time, the body can rebuild the lost blood (Eskandari-Khanghahi et al., 2018). In addition, there are eight major blood types: A+, A-, B+, B-, AB+, AB-, O+, and O- which all have some derivation with different lifetimes and they need to be held in specific conditions. Derivation of blood, which is mainly referred to the whole blood, results in 5 main products: whole blood, red blood cells (35 to 42 days expiration time), white blood cells (WBS), platelets (5-7 days expiration time) and plasma (1 year), which have specific characteristics and usages (Katsaliaki, 2008; Zahiri et al., 2018, Habibi-Kouchaksaraei et al., 2018). The blood should be stored in a cool place such as a refrigerator. Therefore, we need some refrigerators for transporting them (Habibi-Kouchaksaraei et al., 2018). Therefore, holding a sufficient amount of blood and managing it to meet demands is an important and vital matter (Beliën and Forcé, 2012).

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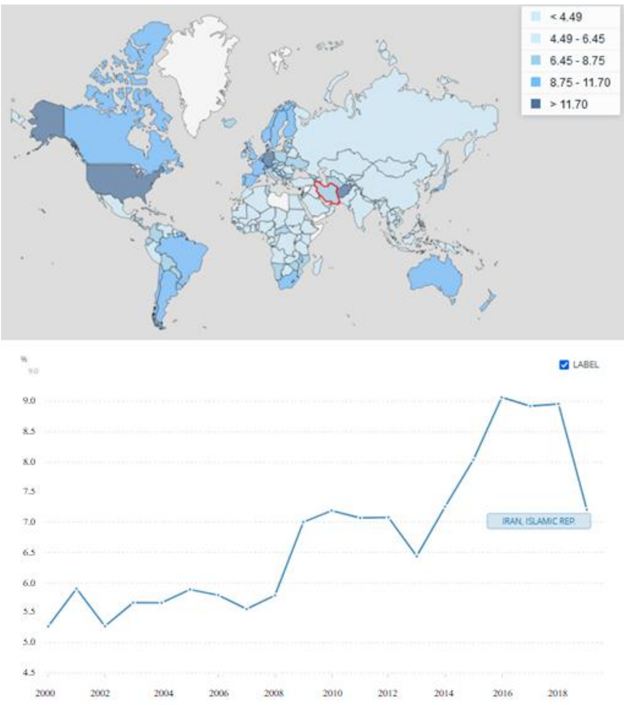


Fig. 1. Iran's health expenditure (% of GDP) World Health Organization Global Health Expenditure database (apps.who.int/nha/database)

Blood supply chain is defined as a network of facilities in order to supply blood to final consumers at the appropriate time and location (Sarrafha et al., 2014). Blood supply is one of the most challenging problems in the blood supply chain system. The Blood Supply Chain (BSC) manages the flow of blood products from donors to patients through five categories: donors, mobile collection sites (MCSs), blood centers (BCs), demand nodes, and patients (Piraban et al., 2019). These must be coordinated to perform the six main processes associated with blood donation: collection, testing, component processing, storage, distribution, and transfusion. The main blood components are red blood cells (RBCs), platelets (PLTs), plasma, and cryoprecipitate antihemophilic factor (cryo) (Pirabán et al., 2019).In other words, collection of blood from donors, testing for any infection such as Hepatitis A, B or C, HIV, or West Nile Virus (Rajendran and Ravindran, 2019) and processing to its derivatives in the blood centers, then delivering them to hospitals, which ultimately deliver these blood derivatives to patients all perform in the blood supply chain. In a geographical area, a blood center is responsible to provide blood products to hospitals. To do this, a blood sampling schedule is set up at potential blood donation sites several months in advance. When the blood donation deadline is near, donors request blood donations through these locations. Mobile blood collection facilities with service, medical, and equipment staff will be sent to these locations according to the schedule. Decisions are then made to derive different components from whole blood. The received whole blood is sent to processing centers for registration and maintenance and finally tested for screening for various viruses and diseases. The resulting components are stored and properly sent to hospitals based on their inventory needs. Finally, the hospital decides when and how these blood components can be used (Zuhairi et al., 2018).

To avoid costs caused by blood outdated, shortages, and any deficiencies in blood supply chains, efficient blood supply chain management comes to great significance (Ghatreh Samani et al., 2019). So, in this research, a network is considered that both shortages and surplus of blood in hospitals and distribution centers are undesirable. Also, by considering the lateral transmission between hospitals and distribution centers, in such a way that if the demand increases for any reason and the inventory level decreases momentarily, the shortage can be compensated by other hospitals and even apheresis centers by transverse transfer (hospital priority). This is also true of the shortage of fixed distribution centers. Therefore, both inventory optimization and shortage prevention are considered. The increase in inventory, which results in the deterioration of blood products in hospitals, is adjusted in this way and the loss of this vital product is prevented. The next issue that brings the research output closer to the real world is the multiplicity of blood products, which, along with lateral transmission between hospitals and distribution centers, can be a novel issue in dealing with shortages and preventing surplus blood items that have a different shelf life. This research proposed a multi-objective mathematical model (minimization of total costs - minimization of the total delivery time of blood units - minimization of maximum non-estimated demand of hospitals) for development of a blood supply chain. In the present case, the nature of objective functions is to reduce the types of costs, which include; costs of holding, excess inventory, and shortage. Since the donation of blood is almost voluntary, supplying blood is not certain and there is always uncertainty. Thus, the amount of inventory in blood products is often uncertain. Optimizing the existing problem includes simultaneously reducing inventory costs in distribution centers and hospitals and reducing shortage costs in the face of extant demand. This study tries to minimize the average lack of demand coverage for hospitals (in order of priority) using lateral transfer and lack of inventory for blood centers by considering lateral transfer between distribution centers. Due to the variety of the blood products and their different perishability time, the life time period of each product and their related costs should be considered as a constraint in modelling.

The remainder of the paper is structured as follows. In Section 2, we present a literature review on blood supply chain studies. The research methodology and the proposed research framework are presented in Section 3. Section 4 described the developed model in a real case study and the results are discussed. The conclusions and some future research directions are presented in section 5.

## 2. Literature Review

In recent years, global healthcare has focused on improving supply chains. The main reasons for this focus are the reduction of healthcare costs and waste of resources while maintaining the level of customer service, patient safety, and general health. Blood is one of the most vital health products that has not yet found a replacement. Although there are considerable improvements in superseding blood and its products, there remains a need for more blood donations (Habibi-Kouchaksaraei et al., 2018). Therefore, the supply chain of blood products is a highly complex one because of the many decisions involving supply collection, inventory levels, waste levels, and transfusion decisions (Kenan and Diabat, 2022).

The blood supply chain is generally divided into 5 echelons: (1) blood collection, (2) blood testing, (2) blood processing, (4) blood storage, and (5) blood distribution. The process of receiving blood from donors is called blood collection. When blood is collected, should be tested to screen its viruses and diseases in terms of blood testing. Next, in the processing phase, whole blood should be processed to separate its derivations such as red blood cells (RBC), plasma, and platelets. Once available for use, the blood derivations are allocated to inventories, typically at blood banks and hospitals, being ready to be distributed and used. The process of supplying the amount of blood required to satisfy the demand is examined during the distribution phase. Managing the BSC encompasses the major challenge of balancing storage and wastage of the blood units. Given the perishable nature of this product, storing an excessive number of blood units could result in the wastage of this limited resource. On the other hand, having shortages may result in tragic outcomes since lives can be lost if no stock is available when it is needed (Dillon et al., 2017).

Blood supply chain studies began in the 1960s. Jacobs et al. (1996) presented a model in their research. In the field of location-allocation of facilities in the blood supply chain and relocation and network configuration and facilities (Beliën and Force, 2012). Wang and Ma (2015) proposed an approach based on the age of blood units in which they compared the two modes of age and the amount of inventory in the blood bank of hospitals, due to decreasing inventory or increasing the age of blood units exchanged between hospitals when there is a shortage. Habibi-Kouchaksaraei et al. (2018) proposed a robust optimization model for designing a bi-objective multi-period three echelons supply chain network of blood in a disaster. The proposed model determines the number and location of facilities and the best strategy to allocate them under three different scenarios, while the goals are to minimize costs and shortages of blood.

Hosseini Motlagh et al. (2019) presented a two-objective mixed linear programming model to design the collection, production, and distribution network of blood under uncertain conditions and through a multi-period planning horizon in which strategic and tactical decisions are necessary. Dutta and Nagurney (2019) proposed a multitiered competitive supply chain network model for the blood banking industry, that captures the economic interactions among three blood service organizations, the hospitals or medical centers, and the player groups. They modeled the behavior of each category and used the theory of variational inequalities to derive the equilibrium conditions for the entire supply chain. In a research, Piraban et al. (2019) investigated the published papers dealing with the blood supply chains between 2005 and 2019 and methods of blood supply chain management. They proposed a categorization scheme based on the: decision-making environments, issues in the design of the blood supply chain, operational processes, planning decisions, modeling and solution methods, and data characteristics. Kenan and Diabat (2022) formulated the blood products supply chain problem in disasters using two-stage stochastic programming where the uncertainty of both demand and supply is considered. Solving the model with heuristic algorithms showed that bigger capacities of permanent collection facilities are favored over the mobility of temporary facilities while accounting for blood substitution and age-based demand in the planning phase reduced shortages significantly. Shih et al. (2023) developed a MCDM model for platelet inventory management along the blood supply chain. The proposed model minimizes: total supply chain costs, unit outdated, and unit shortage under demand uncertainty. Aghsami et al. (2023) proposed a novel mathematical model for Blood Supply Chains, which minimizes the total costs and maximizes donor satisfaction by reducing the system's waiting time. A real-world case study is presented and solved using a new meta-heuristic algorithm to illustrate the model's applicability. Setiawati et al. (2024) studied several variables, such as people, processes, technology, and partners in the management of hospital supply chains. The variables were modeled in causal loop diagrams to present the interrelationships between decision factors. Entezari et al (2024) proposed a bi-objective model to minimize blood shortage and cost and simultaneously. This study considered the position of blood amenities, allocation of donors, as well as different facilities and blood centers, collection, production, and testing of perishable blood components of multiple blood types, demand uncertainty, and time-dependent routing decisions.

Table (1) summarized the current studies on blood supply network s where conducted in the last decade.

Table 1.
Recent studies in blood supply chain management

| Authors | Method | Time/ Objective/ Solution | Type of blood product | Measure | Data |
|---|---|---|---|---|---|
| Zahiri and et al. (2015) | MILP | MP/SO/EM | WB | Cost | Fuzzy-Robust |
| Gunpinar and Centeno (2015) | INPL, SIM | MP/SO/MM | RBC | Outdate | Stochastic |
| Şahinyazan et al. (2015) | LP | MP/MO/MM | WB | Cost | - |
| Elalouf et al. (2015) | MILP | MP/SO/EM | WB | Cost | - |
| Fereiduni and Shahanaghi (2016) | SIM | MP/SO/- | WB | Cost | Robust |
| Yousefi Nejad Attari et al. (2016) | SIM | MP/MO/- | WB | Cost, Shortage, Outdate, Freshness | Robust-Stochastic |
| Ramezanian and Behboodi (2017) | MILP | MP/SO/EM | WB | Cost | Robust |
| Puranam et al. (2017) | DP, SIM | MP/SO/- | RBC | Cost | - |
| Dillon et al. (2017) | MILP | MP/SO/EM | RBC | Cost, Shortage, Outdate | Stochastic |
| Rajendran and Ravindran (2017) | MILP | MP/SO/EM | PLT | Cost, Shortage, Outdate | Stochastic |
| Fahimnia et al. (2017) | SP | MP/MO/EM | WB | Cost, Time | Stochastic |
| Masoumi et al. (2017) | DP, SIM | MP/SO/- | WB, RBC | Cost, Time | - |
| Ghatreh Samani et al. (2018) | MILP | MP/SO/MM | RB, PLT, PLS | Cost, Shortage, Outdate | Stochastic |
| Osorio et al. (2018) | MILP | MP/MO/- | WB | Cost, Shortage, Outdate | Stochastic |
| Heidari-Fathian and Pasandideh (2018) | MILP | MP/MO/MM | RB | Cost, Shortage, Outdate, Freshness | Robust |
| Habibi-Kouchaksaraei et al. (2018) | GP | MP/MO/EM | WB | Cost, Shortage | Robust |
| Hosseinifard and Abbasi (2018) | SIM | SP/SO/- | WB | Time | Stochastic |
| Eskandari-Khanghah e al. (2018) | MILP | MP/MO/MM | PLT | Cost, Shortage, Outdate, Freshness | - |
| Rahmani (2019) | DP, SIM | MP/MO/- | WB | Shortage, Outdate | Robust |
| Ghatreh Samani et al. (2019) | MILP | MP/MO/EM | WB, PLT, RB, PLS | Cost, Shortage, Outdate, Freshness | Fuzzy-Robust |
| Xiao and Song (2019) | MILP | MP/MO/EM | WB | Cost, Time | - |
| Rajendran and Ravindran (2019) | IP | MP/SO/MM | PLT | Cost, Shortage, Outdate | Stochastic |
| Pritha and Nagurney (2019) | IP | MP/SO/EM | RB, PLT, PLS | Cost, Shortage | - |
| Gilani Larimi and Yaghoubi (2019) | SP2 | MP/MO/EM | PLT | Cost, Shortage, Outdate, Freshness | Fuzzy-Robust |
| Gilani Larimi et al. (2019) | MILP | MP/MO/- | PLT | Cost, Shortage, Outdate, Freshness | Robust-stochastic |
| Fanoodi et al. (2019) | SIM | SP/SO/EM | PLT | Cost, Freshness | Stochastic |
| dehghani et al. (2019) | MILP | MP/SO/- | WB | Cost, Shortage, Outdate | Stochastic |
| Ezugwu et al. (2019) | DP | MP/SO/MM | WB | Cost, Shortage, Outdate | - |
| Hosseini-Motlagh et al. (2019) | MILP | MP/MO/- | WB, PLT, RB, PLS | Cost, Shortage, Outdate, Freshness | Fuzzy-Robust-Stochastic |
| Samani (2019) | MILP | MP/SO/EM | PLT, RB, PLS | Cost | Fuzzy-Robust |
| Salehi et al. (2019) | SP2 | MP/SO/- | WB | Cost | Robust-Stochastic |
| Nezamoddini et al. (2020) | SIM | MP/MO/EM | WB | Risk | Robust |
| Ghorashi et al. (2020) | SIM | MP/MO/MM | WB | Cost, Time | - |
| Haghjoo et al. (2020) | SIM | MP/SO/MM | WB | Cost, Shortage, Outdate | Robust |
| Khalilpourazari et al. (2020) | SIM | MP/MO/- | WB | Cost, Time, Risk | - |
| Hamdan and Diabat (2020) | SP2 | MP/MO/- | WB, PLT, RB, PLS | Time, Cost | Robust |
| Wang and Chen (2020) | SP2 | MP/SO/- | WB | Cost | Stochastic |
| Fallahi et al. (2021) | | SP/MO/MM | WB | Quality, | - |
| Asadpour et al. (2022) | Review | -/-/- | - | - | - |
| Kenan and Diabat (2022) | SP2 | SP/MO/MM | PLT, RB, PLS | Capacity, Shortage | Stochastic |
| Torrado and Barbosa-Póvoa (2022) | Review | -/-/- | - | - | - |
| Suen et al. (2023) | SP2 | SP/MO/ | PLT | Shortage, Wastage | Stochastic |
| Shih et al. (2023) | MCDM,MOP | SP/MO/GP | PLT | Cost, Shortage, Outdate | - |
| Mansur et al. (2023) | MILP | SP/SO/- | WB, PLT, RB, PLS | Profit | - |
| Meneses et al. (2023) | Review | -/-/- | - | - | - |
| Aghsami et al. (2023) | MO | SP/MO/MM | WB | Costs, Satisfaction, Time | - |
| Entezari et al. (2024) | SP2 | SP/MO/MM | WB, PLT, RB, PLS | Cost, Shortage | Stochastic |
| Ala et al. (2024) | MILP | SP/MO/GP | WB | Cost, Distance, Time | Robust |
| Hosseini-Motlagh et al. (2024) | RHP | SP/MO/DP | - | Demand, Cost, Time | Robust |

**SP**: Single Period, **MP**: Multi-Period, **SO**: Single Objective, **MO**: Multi-Objective, **EM**: Exact Method(s), **MM**: Meta-heuristic Method(s), **IP**: Integer Programming, **DP**: Dynamic Programming, **GP**: Goal Programming, **MILP**: Mix Integer Linear Programming, **INLP**: Integer Non-Linear Programming, **MINLP**: Mix Integer Non-Linear Programming, **SP2**: Stochastic Programming, **WB**: Whole Blood, **PLT**: Platelets, **RB**: Red Blood, **PLS**: Plasma.

Reviewing the literature, it did not find any research which considers lateral transmission in blood supply chain in situations where hospital demands have different priorities, and the level of inventory surplus/ shortage is equally important. Therefore, optimizing the inventory levels in blood consumption centers (hospitals) prevents blood loss or expiration as much as possible. Also, due to the hospitals' knowledge about the blood exchange network, a level of confidence in receiving blood in case of emergency is considered for the hospital, which causes them to avoid excess demand, which reduces maintenance costs. Also, knowing that the inventory level of distribution centers (blood transfusion) together with the inventory of hospitals leads them to provide inventory from the other distribution centers (blood transfusion). In this case, the excess inventory should be transferred to other distribution centers or hospitals. With all the interpretations, the inclusion of different blood products (more than one product) with different consumption period, increase the need for research in this field.

The novelty of the study is as follows: (a) considering the issue of blood type compatibility in meeting the demand in such a way that in the case of deficiency of one blood type, other substitute blood groups could be used; (b) considering the blood group delivery and allocation queuing system in laboratories and blood banks, in such a way that donates with rare blood groups, spend less time in the laboratory and blood bank to be sent immediately based on demand; (c) considering blood loss in the laboratory; (d) considering the transfer of products between demand centers as the sub-network, and determining model parameters of the such as demand parameter, blood donation and delivery time of blood products between network components, which are uncertain. The proposed model has three objectives. The first objective function is to minimize the total cost. Due to the high importance of the time of sending blood units, the second objective function is to minimize the total time sending blood units. The third objective function is to minimize the maximum non-estimated demand for hospitals in each period. Also, to innovate and improve the model and bring it closer to reality, budget constraints for the purchase of raw materials and products, as well as the production of finished products are considered probable.

## 3. Research Method

This paper proposed a multi-objective mathematical model for minimizing the total cost, minimizing the total delivery time of blood units, and minimizing the maximum unmet demand of hospitals in the blood supply chain. In the real word problems, the nature of objective functions is to reduce the types of costs which includes cost of inventory maintenance, excess inventory, and shortage. The nature of blood supply and demand problems and its inventory system are often uncertain. Optimizing the existing problem includes simultaneously reducing inventory maintenance costs in distribution centers and hospitals and reducing shortage costs in the face of instant demand. This study attemps to minimize the average of uncoveraged demand of hospitals (according to the priority) using lateral transmission and shortage of inventory in blood centers by considering lateral transmission among distribution centers. Due to the variety of the products and their different perishability times, usage time and its related costs also should be considered as a limitation in modelling process.

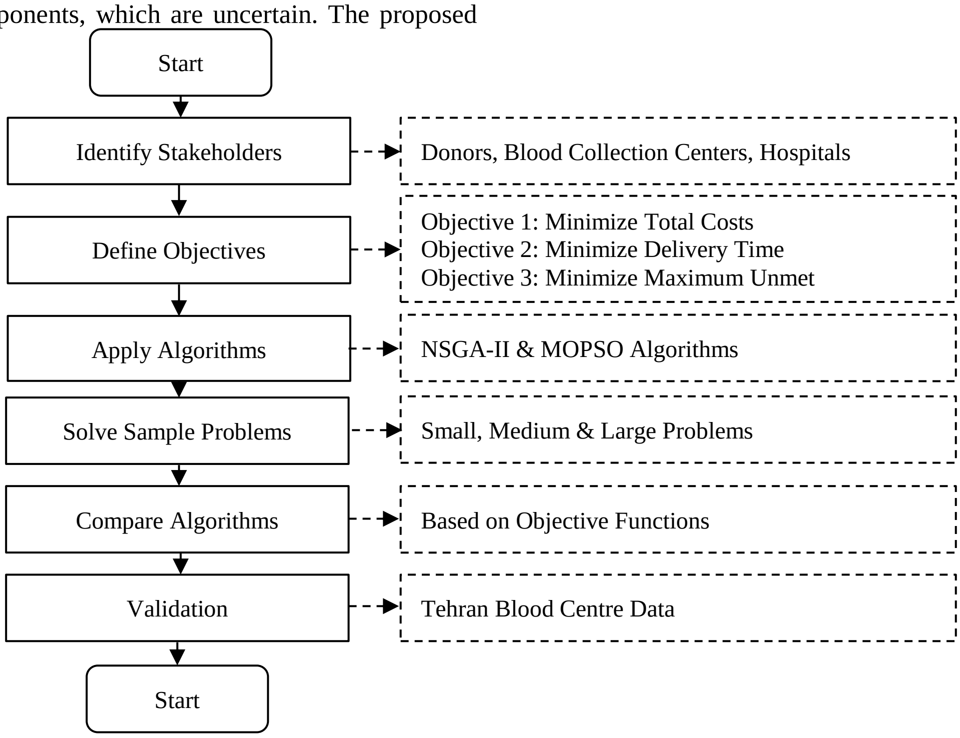


Fig. 2. Research framework

The required data to implement the real world problem, attained in cooperation with regional office of the Blood Transfusion Organization in Tehran province, which has designed a comprehensive database system to record and track the daya of blood units called the Negareh system. This information is collected daily from all hospitals in Tehran and is stored in this database.
Since, for solving the proposed model, several problems with different size will be used, different methods could be used to solve them. Considering that in the literature, such problems are among Np-hard problems, and exact methods could only solve small and medium size problems, two multi objective optimization algorithm namely NSGA-II and MOPSO the model uses multi-objective optimization algorithms. The required data are gathered trough the Negareh system as the database of the Blood Transfusion Organization in Tehran province, which stores blood related data for all the hospitals of Tehran Province. Fig (2) illustrates the steps of solving the blood supply network problem as described.

*3.1. Proposed model*

Each blood supply chain includes three levels: donors, banks or blood centers, and customers (hospitals). In this study, all three levels of the blood supply chain are considered.

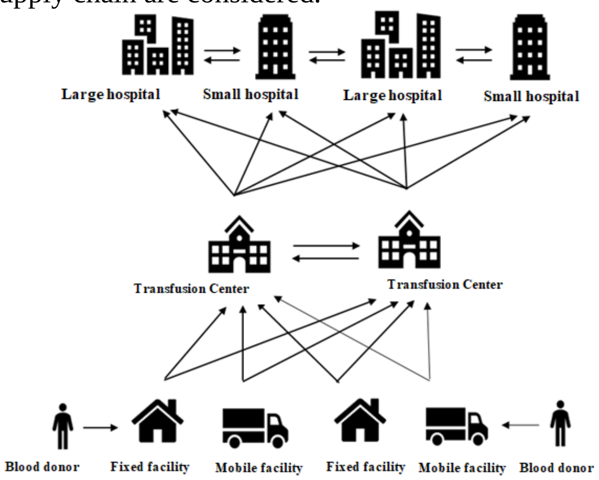


Fig 3. Blood supply chain studied in the research

- *Problem assumptions*

1. Fixed centers (Blood Transfusion Organization) and placement of mobile facilities and fixed facilities are predetermined.
2. Sampling is done by both fixed and mobile facilities.
3. Planning for blood donors is considered regionally.
4. Blood units are sent to fixed blood centers in each period of mobile and fixed facilities.
5. This issue is considered a multi-product (types of blood groups and other blood products).
6. Mobile and fixed facilities and fixed centers (blood banks or Red Crescent Organization) have different capacities.
7. The age of blood units received from fixed centers (Blood Transfusion Organization) is determined and varies over time.
8. Lateral transfer between hospitals and fixed centers (Blood Transfusion Organization) is possible.
9. Demand is random (a combination of specific demand and emergency demand).
10. Lack and surplus of inventory are not allowed.
11. If demand is not met due to a lack of inventory, the system will incur a shortage penalty.
12. If a unit of blood expires, the system will incur a waste cost.
13. The demand for each blood type is met by the group itself and the medically authorized groups.

- *Model indices*

We define the model indices as follows:

| | | |
|---|---|---|
| i | Donor Group Collection Index | $i = 1.2. \dots . \mathrm{I}$ |
| c | Blood Centers Index | $c = 1.2. \dots . \mathrm{C}$ |
| j | Index of Mobile Facility Locations | $j = 1.2. \dots . \mathrm{J}$ |
| p | Index of Fixed Facility Locations | $p = 1.2. \dots . K$ |
| t | Time Period Index | $t = 1.2. \dots . T$ |
| h | Hospital Complex Index | $h = 1.2. \dots . H$ |

- *Model parameters*

The model parameters are defined as follows:

| | |
|---|---|
| $N_t$ | Number of facilities required in period t |
| $X_P$ | Has a value of one if the fixed facility is in place p; otherwise zero |
| $Y^1_{ijt}$ | If in period t, the blood donor group located at location i is assigned to a mobile facility located at location j, has a value of one; otherwise zero |
| $Y^2_{ipt}$ | If in time period t, the blood donor group located at location i is assigned to a fixed facility located at location p, it has a value of one; otherwise zero |
| $Z_{j_1 j_2 t}$ | Has a value of one if the mobile facility of blood collection is in position j1 in period 1-t and is used in period t in position j2; otherwise zero |
| $\mathrm{la}^1_{cc't}$ | If lateral transfers are made between blood centers c and c', has a value of one; otherwise zero |
| $\mathrm{la}^2_{hh't}$ | If lateral transfers are made between hospitals h and h', it has a value of one; otherwise zero |
| $\mathrm{Q}^1_{ijt}$ | The rate of transfer of blood packets from a blood donor group located at location i to a mobile facility located at location j during period t |
| $\mathrm{Q}^2_{ipt}$ | The rate of transfer of blood packets from the blood donor group located at location i to the fixed facility located at location p in period t |

| | |
|---|---|
| $Q^3_{jct}$ | The rate of transfer of blood packages from a mobile facility located at location j to blood center c during period t |
| $Q^4_{pct}$ | The rate of transfer of blood packets from a fixed facility located at location p to blood center c during period t |
| $Q^5_{cht}$ | The rate of blood package transfer from blood center c to hm hospital in period t |
| $LT^1_{cc't}$ | The transmission rate of blood packets through lateral transfers between blood centers c and c' |
| $LT^2_{hh't}$ | The transmission rate of blood packages through lateral transfers between h and hospitals |
| $I^1_{pt}$ | The amount of blood inventory in a fixed facility located at location p at the end of period t |
| $I^2_{ct}$ | Level of blood supply in the center of blood c at the end of period t |
| $I^3_{ht}$ | Blood inventory level in hospital h at the end of period t |
| $\delta_{ht}$ | Unmet demand in hospital h at the end of period t |

*- Decision variables*

Model decision variables were defined as follows:

| | |
|---|---|
| $f_P$ | The cost of constructing a fixed facility on site p |
| $A^1_t$ | The cost of maintaining each unit of blood in a fixed facility over a period of t |
| $A^2_t$ | The cost of maintaining each unit of blood in blood centers during the period t |
| $A^3_t$ | The cost of maintaining each unit of blood in the hospital during the period t |
| $v_{j_1 j_2 t}$ | The cost of moving the mobile blood collection facility from location $j_1$ to location $j_2$ in period t |
| $T^1_{jct}$ | The cost of transferring blood units from mobile facility j to blood center c in period t |
| $T^2_{pct}$ | The cost of transferring blood units from a fixed facility p to a blood center c over a period of t |
| $T^3_{cht}$ | The cost of transferring blood units from blood center c to hospital h in period t |
| $T^4_{cc't}$ | The cost of transferring blood units from blood center c to blood center c' in period t |
| $T^5_{hh't}$ | The cost of transferring a unit of blood from hospital h to hospital h' during the period t |
| $tim^3_{cht}$ | The time of transfer of blood units from blood center c to hospital h in time period t |
| $tim^4_{cc't}$ | The time of transfer of blood units from the blood center c to the blood center c' in time period t |
| $tim^5_{hh't}$ | Time of transfer of a unit of blood from hospital h to hospital h' in period t |
| $s_h$ | Cost of shortage of blood per unit of hospital |
| $d_{mt}$ | Demand for hospital located at point m in period t |
| $r^1_{ij}$ | The distance between the blood donor groups located at point i and the mobile blood collection facility located at location j |
| $r^2_{ip}$ | The distance between the blood donor groups located at point i and the fixed blood collection facility located at location p |
| $b^1_{jt}$ | Fixed facility capacity j over time t |
| $b^2_{pt}$ | The capacity of mobile facilities p in period t |
| $b^3_{ct}$ | The capacity of blood center c in period t |
| $b^5_{ht}$ | The capacity of hospital center h in period t |
| $b^4_{it}$ | Blood donation capacity by blood donors located at location i in period t |
| $cap_l$ | Most blood supply from blood group l in period t |
| $w_1$ | The radius of coverage of mobile facilities |
| $w_2$ | Fixed facility coverage radius |
| $u_c$ | Maximum storage capacity in the blood center c |
| $R^1_{cc'}$ | Distance between blood centers c and c' |
| $R^2_{hh'}$ | The distance between hospitals h and h' |
| $R^1_0$ | The radius of coverage for lateral transfers between blood centers |
| $R^2_0$ | The radius of coverage for lateral transfers between hospitals |
| $d_{ht}$ | The demand of h hospital in period t |
| M | Very big number |

*- Objective functions*

The first objective function minimizes total costs including the cost of constructing a fixed facility, the cost of moving a mobile blood collection facility, the cost of transferring blood units from mobile facilities to blood centers, the cost of transferring blood units from a fixed facility to blood centers, the cost of transferring blood units from blood centers to hospitals, the cost of transferring blood units between blood centers (lateral transfer between blood centers), the cost of transferring blood units between hospitals (lateral transfer), the cost of maintaining each blood unit in a fixed facility, the cost of maintenance of each blood unit in blood centers and the cost of maintaining each blood unit in hospitals.

$$\begin{aligned}\min \ & \sum_{p} f_P X_P + \sum_{t}\sum_{j_2}\sum_{j_1} v_{j_1 j_2 t} Z_{j_1 j_2 t} \\ & + \sum_{t}\sum_{c}\sum_{j} \mathrm{T}^1_{jct}\, \mathrm{Q}^3_{jct} \\ & + \sum_{t}\sum_{c}\sum_{p} \mathrm{T}^2_{pct}\, \mathrm{Q}^4_{pct} \\ & + \sum_{t}\sum_{h}\sum_{c} \mathrm{T}^3_{cht}\, \mathrm{Q}^5_{cht} \\ & + \sum_{t}\sum_{c'}\sum_{c} \mathrm{T}^4_{cc't}\, \mathrm{LT}^1_{cc't} \\ & + \sum_{t}\sum_{h'}\sum_{h} \mathrm{T}^5_{hh't}\, \mathrm{LT}^2_{hh't} \\ & + \sum_{t}\sum_{p} A^1_t\, \mathrm{I}^1_{pt} \\ & + \sum_{t}\sum_{c} A^2_t\, \mathrm{I}^2_{ct} \\ & + \sum_{t}\sum_{h} A^3_t\, \mathrm{I}^3_{ht}\end{aligned} \tag{1}$$

Second objective function minimizes the total time of sending blood units including the time of transfer of blood units from blood centers to hospitals + the time of transfering blood units between blood centers, the transfer of blood units between hospitals (lateral transfer between hospitals).

$$\begin{aligned} min \ & \sum_{t}\sum_{h}\sum_{c} tim^3_{cht}\, Q^5_{cht} \\ & + \sum_{t}\sum_{c'}\sum_{c} tim^4_{cc't}\, LT^1_{cc't} \\ & + \sum_{t}\sum_{h'}\sum_{h} tim^5_{hh't}\, LT^2_{hh't}\end{aligned} \tag{2}$$

The third objective function minimizes the maximum unmet demand of hospitals in each period.

$$\min_t (\max_h \delta_{ht}) \tag{3}$$

Constraint 1 indicates that at maximum one of the mobile blood collection facilities in period 1-t can be used in period t at location $j_2$.

$$\sum_{j_1} Z_{j_1 j_2 t} \le 1 \quad . \quad \forall j_2 . t \tag{4}$$

Constraint 2 indicates that the number of facilities in question in period t is equal to the total mobile blood collection facility in period 1-t to be used in period t in one of the available locations.

$$\sum_{j_2}\sum_{j_1} Z_{j_1 j_2 t} = N_t \quad . \quad \forall t \tag{5}$$

Constraint 3 indicates that the mobile blood collection facility in the period 1-t at location j1 can go to one of the other available locations if it comes to the j1 location in step 2-t.

$$\sum_{\mathrm{j}} \mathrm{Z}_{\mathrm{j_1\, j\, t}} \le \sum_{\mathrm{j}} \mathrm{Z}_{\mathrm{jj_1 (t-1)}} \quad . \quad \forall \mathrm{t} . \mathrm{j_1} \tag{6}$$

Constraint 4 indicates that in each time period t, any one of the blood donor groups is assigned to a maximum of one mobile or fixed facility. The radius of its coverage should be facilitated.

$$\sum_{j} Y^1_{ijt} + \sum_{p} Y^2_{ipt} \le 1 \quad . \quad \forall i . t \tag{7}$$

Constraint 5 states that in each time period, due to the presence of a mobile facility in location i and its coverage radius, should be assigned to the same mobile facility.

$$Y^1_{ijt}\, \mathrm{r}^1_{ij} \le \mathrm{w}_1 \sum_{j_2} Z_{j_1\, j\, t} \quad . \quad \forall i . j . t \tag{8}$$

Constraint 6 states that in each time period, due to the presence of a fixed facility at location p and its coverage radius, should be assigned to the same fixed facility.

$$Y^2_{ipt}\, \mathrm{r}^1_{ip} \le \mathrm{w}_2 X_P \quad . \ \forall i . p . t \tag{9}$$

Constraints 7-8 indicate that in each time period, if the blood donor group is located at location i can donate blood packages to a mobile or fixed facility (at a maximum of one of them), that group will donate to the facility if it was assigned to the same facility.

$$\begin{aligned} \mathrm{Q}^1_{ijt} &\le M * Y^1_{ijt} \ . \ \forall i . j . t \\ \mathrm{Q}^2_{ipt} &\le M * Y^2_{ipt} \ . \ \forall i . p . t \end{aligned} \tag{10}$$

Constraint 9 states that in each time period, the number of blood transfusions of the donor group located at location i to a mobile or fixed facility must be less than the capacity of the blood donor.

$$\sum_{i} \mathrm{Q}^1_{ijt} + \sum_{i} \mathrm{Q}^2_{ipt} \le \mathrm{b}^4_{it} \quad . \quad \forall i . j . t \tag{11}$$

Constraints 10-11 indicate that in each time period, the amount of mobile or fixed facility received from donors should be less than the capacity of that facility.

$$\begin{aligned} \sum_{i} \mathrm{Q}^1_{ijt} &\le \mathrm{b}^1_{jt} \quad . \quad \forall t . j \\ \sum_{i} \mathrm{Q}^2_{ipt} &\le \mathrm{b}^2_{pt} \quad . \quad \forall t . p \end{aligned} \tag{12}$$

Constraint 12 states that in each time period, the amount received by each blood center from the facility must be less than or equal to the capacity of that blood center.

$$\sum_{j} \mathrm{Q}^3_{jct} + \sum_{p} \mathrm{Q}^4_{pct} \le \mathrm{b}^3_{ct} \quad . \quad \forall t . c \tag{13}$$

Constraint 13 indicates that in each period of time, the amount received by each hospital from the blood centers should be less than or equal to the capacity of that hospital.

$$\sum_{h} \mathrm{Q}^5_{cht} \le \mathrm{b}^5_{ht} \quad . \quad \forall t . h \tag{14}$$

Constraints 14–15 indicate that in each time period, blood packets are transferred through lateral transfers between blood centers c and c' (14); if the distance between the two blood centers is less than or equal to the radius of coverage for lateral transfers between blood centers (13).

$$\begin{aligned} R^1_{cc'} * \mathrm{la}^1_{cc't} &\le R^1_0 \ . \ \forall c . c' . t \\ \mathrm{LT}^1_{cc't} &\le \mathrm{la}^1_{cc't} \ . \ \forall c . c' . t \end{aligned} \tag{15}$$

Constraints 16-17 indicate that in each time period, blood packets are transferred through lateral transfers between hospital h and h' (16); if the distance between the two hospitals is less than or equal to the radius of coverage for lateral transfers between hospitals (15).

$$R^2_{hh'} * \mathrm{la}^2_{hh't} \leq R^2_0 \quad . \quad \forall\, h.h'.t$$
$$\mathrm{LT}^2_{hh't} \leq \mathrm{la}^2_{hh't} \quad . \quad \forall\, h.h'.t \tag{16}$$

Constraint 18 indicates that in each time period, the amount of blood packets sent from each blood center plus the amount of inventory stored at the end of the current period is equal to the amount received from fixed and mobile facilities plus the amount stored at the end of the previous period.

$$\sum_j \mathrm{Q}^3_{jct} + \sum_p \mathrm{Q}^4_{pct} + \sum_{c'} \mathrm{LT}^1_{c'c\,t} + \mathrm{I}^2_{c(t-1)} = \sum_h \mathrm{Q}^5_{cht} + \sum_{c'} \mathrm{LT}^1_{cc't} + \mathrm{I}^2_{ct} \quad . \quad \forall\, t.c \tag{17}$$

Constraint 19 indicates that in each time period, the amount of blood packets sent from each blood center plus the amount of inventory stored at the end of the current period is equal to the amount received from fixed and mobile facilities plus the amount stored at the end of the previous period.

$$\sum_j \mathrm{Q}^5_{cht} + \sum_{h'} \mathrm{LT}^2_{h'h\,t} + \mathrm{I}^3_{h(t-1)} = \sum_h \mathrm{Q}^5_{cht} + \sum_{c'} \mathrm{LT}^2_{hh't} + \mathrm{I}^3_{ht} \quad . \quad \forall\, t.c \tag{18}$$

Constraint 20 indicates that in each time period, the estimated amount of demand is equal to the difference between the demand of each hospital and the total amount received from the blood transfusion centers and lateral transfers to that hospital.

$$\delta_{ht} = \mathrm{d}_{ht} - (\sum_c \mathrm{Q}^5_{cht} + \sum_{h'} \mathrm{LT}^2_{h'h\,t}) \quad . \quad \forall\, t.h \tag{19}$$

### 3.2. NSGA-II algorithm

*Chromosome coding:* The first step in solving a problem with a genetic algorithm is encoding the search space. This requires that each possible answer to the problem be turned into a chromosome containing some genes. The under consideration problem defines three separate chromosomes to define the problem, which are shown in the following matrices.

*The initial population:* After encoding the search space as chromosomes, the next step is implementing the genetic algorithm to create an initial population. In this research, the initial answers are generated randomly and according to the feasibility of the problem.

*Strategies for dealing with constraints***:** In this research, we use correcting strategy to keep feasible the children; in a way that keep the limitations defined in the model according to a procedure.

*Crossover operator:* As mentioned earlier, different crossover operators have been proposed for genetic algorithms. In this research the arithmetic operator for the combination is used as the crossover operator. In this way, the new child is sum of a coefficient of two parents. Equation (20) explains this operator:

$$child\ (1) = round\ (\alpha \times Parent_1 + (1-\alpha)\ Parent_2$$
$$child\ (2) = round\ (\ (1-\alpha) \times Parent_1 + \alpha\ Parent_2) \tag{20}$$

Where $Parent_i$ are the selected parents and α is a coefficient between 0 and 1, and child (i) are the resulting children. Finally, both answers are rounded up to get integer numbers.

*Mutation operator:* In this study, each of the chromosomes could be affected by the mutation operator. A percentage of the population includes these changes.

*Stop condition:* In this study, to stop the search the condition of the maximum number of iterations is used.

## 4. Result & Disscusion

To validate the proposed model in the real world, one-month data from Tehran Blood Center has been used. In Tehran, there are 12 fixed blood collection centers distributed across its 22 districts (See Fig 3). These centers are strategically located to ensure that residents from different parts of the city have easy access to blood donation facilities. Each of these centers operates under the Iranian Blood Transfusion Organization (IBTO) and is equipped to collect, process, and store blood donations from voluntary donors. The Vesal Blood Donation Center is one of the key blood collection facilities in Tehran, located in the central part of the city. In this study, 15 hospitals with the highest demand for blood products according to the data received from Vesal Blood Center, were selected as under study hospitals.

Table 2
Fixed blood collection centers in 22 districts of Tehran

| Blood center | Area | Longitude | Latitude |
|---|---|---|---|
| Tajrish | 1 | 51.43088 | 35.80653 |
| Milad | 2 | 51.37930 | 35.74556 |
| Narmak | 4 | 51.33329 | 35.72087 |
| Sadeghieh | 5 | 51.39755 | 35.72197 |
| Vesal | 6 | 51.35482 | 35.70579 |
| Azadi | 9 | 51.39088 | 35.69675 |
| Vali Asr | 11 | 51.46405 | 35.68842 |
| Pirouzi | 12 | 51.48660 | 35.68754 |
| Afsarieh | 15 | 51.44316 | 35.64589 |
| Khorasan | 16 | 51.44319 | 35.66552 |
| Emam Khomeini | 21 | 51.41942 | 35.68542 |
| Chitgar | 22 | 51.17417 | 35.71473 |

On the other hand, Tehran has 118 hospitals, including public, private, and armed forces hospitals. In this study, 15 out of them, with the highest demand for whole blood and blood products were selected to analysis. Table (3) presents the amount of demand for emergency and other cases in hospitals based on the average days of the week.

Table 3
Demand for emergency and other cases in hospitals

| Hospital | Saturday | | Sunday | | Monday | | Tuesday | | Wednesday | | Thursday | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Emergency | Other Cases | Emergency | Other Cases | Emergency | Other Cases | Emergency | Other Cases | Emergency | Other Cases | Emergency | Other Cases |
| 1 | 15.6 | 21.6 | 13.65 | 23.2 | 14.2 | 21.5 | 11.6 | 19.3 | 5.6 | 8.4 | 4.8 | 6.9 |
| 2 | 19.72 | 26.92 | 17.38 | 28.84 | 18.04 | 26.8 | 14.92 | 24.16 | 7.72 | 11.08 | 6.76 | 9.28 |
| 3 | 13.04 | 18.44 | 11.285 | 19.88 | 11.78 | 18.35 | 9.44 | 16.37 | 4.04 | 6.56 | 3.32 | 5.21 |
| 4 | 18.16 | 24.76 | 16.015 | 26.52 | 16.62 | 24.65 | 13.76 | 22.23 | 7.16 | 10.24 | 6.28 | 8.59 |
| 5 | 17.068 | 23.248 | 15.0595 | 24.896 | 15.626 | 23.145 | 12.948 | 20.879 | 6.768 | 9.652 | 5.944 | 8.107 |
| 6 | 14.26 | 19.36 | 12.6025 | 20.72 | 13.07 | 19.275 | 10.86 | 17.405 | 5.76 | 8.14 | 5.08 | 6.865 |
| 7 | 16.04 | 21.44 | 14.285 | 22.88 | 14.78 | 21.35 | 12.44 | 19.37 | 7.04 | 9.56 | 6.32 | 8.21 |
| 8 | 7.86 | 11.46 | 6.69 | 12.42 | 7.02 | 11.4 | 5.46 | 10.08 | 1.86 | 3.54 | 1.38 | 2.64 |
| 9 | 8.8 | 11.8 | 7.825 | 12.6 | 8.1 | 11.75 | 6.8 | 10.65 | 3.8 | 5.2 | 3.4 | 4.45 |
| 10 | 21.72 | 28.92 | 19.38 | 30.84 | 20.04 | 28.8 | 16.92 | 26.16 | 9.72 | 13.08 | 8.76 | 11.28 |
| 11 | 21.28 | 29.08 | 18.745 | 31.16 | 19.46 | 28.95 | 16.08 | 26.09 | 8.28 | 11.92 | 7.24 | 9.97 |
| 12 | 24.4 | 33.4 | 21.475 | 35.8 | 22.3 | 33.25 | 18.4 | 29.95 | 9.4 | 13.6 | 8.2 | 11.35 |
| 13 | 13.04 | 18.44 | 11.285 | 19.88 | 11.78 | 18.35 | 9.44 | 16.37 | 4.04 | 6.56 | 3.32 | 5.21 |
| 14 | 8.24 | 10.64 | 7.46 | 11.28 | 7.68 | 10.6 | 6.64 | 9.72 | 4.24 | 5.36 | 3.92 | 4.76 |
| 15 | 15.48 | 20.28 | 13.92 | 21.56 | 14.36 | 20.2 | 12.28 | 18.44 | 7.48 | 9.72 | 6.84 | 8.52 |

Considering the assumption of lateral transmission, Table (4) provides information about the distances among the hospitals.

Table 4
Distances between hospitals (KM)

| Hospital | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 6.5 | 8.3 | 7.2 | 5.9 | 10.8 | 9.6 | 6.7 | 11.5 | 9.2 | 11.3 | 7.6 | 8.9 | 10.5 | 12.6 |
| 2 | - | 0 | 15.28 | 13.52 | 11.44 | 19.28 | 17.36 | 12.72 | 20.4 | 16.72 | 20.08 | 14.16 | 16.24 | 18.8 | 22.16 |
| 3 | - | - | 0 | 12.52 | 10.44 | 18.28 | 16.36 | 11.72 | 19.4 | 15.72 | 19.08 | 13.16 | 15.24 | 17.8 | 21.16 |
| 4 | - | - | - | 0 | 7.26 | 14.12 | 12.44 | 8.38 | 15.1 | 11.88 | 14.82 | 9.64 | 11.46 | 13.7 | 16.64 |
| 5 | - | - | - | - | 0 | 10.72 | 9.64 | 7.03 | 11.35 | 9.28 | 11.17 | 7.84 | 9.01 | 10.45 | 12.34 |
| 6 | - | - | - | - | - | 0 | 18.28 | 13.06 | 21.7 | 17.56 | 21.34 | 14.68 | 17.02 | 19.9 | 23.68 |
| 7 | - | - | - | - | - | - | 0 | 12.4 | 22 | 17.4 | 21.6 | 14.2 | 16.8 | 20 | 24.2 |
| 8 | - | - | - | - | - | - | - | 0 | 18.75 | 15.3 | 18.45 | 12.9 | 14.85 | 17.25 | 20.4 |
| 9 | - | - | - | - | - | - | - | - | 0 | 17.32 | 21.73 | 13.96 | 16.69 | 20.05 | 24.46 |
| 10 | - | - | - | - | - | - | - | - | - | 0 | 23.73 | 15.96 | 18.69 | 22.05 | 26.46 |
| 11 | - | - | - | - | - | - | - | - | - | - | 0 | 8.84 | 10.01 | 11.45 | 13.34 |
| 12 | - | - | - | - | - | - | - | - | - | - | - | 0 | 8.654 | 10.03 | 11.836 |
| 13 | - | - | - | - | - | - | - | - | - | - | - | - | 0 | 20 | 24.2 |
| 14 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0 | 19.64 |
| 15 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 0 |

Information on the distances between the blood center and the hospitals are provided in Table (5).
Regarding the number of blood transfusion centers in Tehran, there are a total of 16 fixed bases and 3 mobile teams that are geographically active in most areas of Tehran, including blood collection units. Information on the distances between the blood center and the fixed facility is provided in the table (6).

Table 5
Distances between blood centers and hospitals

| Fixed Facility | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blood Center | 10.3 | 6.8 | 9.5 | 11.6 | 12.3 | 15.4 | 17.25 | 8.4 | 7.9 | 10.2 | 9.8 | 13.6 | 11.4 | 10.7 | 3.9 |

Table 6
Model Parameters

| Parameter | Description | Value | Parameter | Description | Value |
|---|---|---|---|---|---|
| $f_P$ | The cost of constructing a fixed facility on site p | 35000000 | $r^2_{ip}$ | The distance between the blood donor groups located at point i and the fixed blood collection facility located at location p | $uniform$ (20,30) |
| $A^1_t$ | The cost of maintaining each unit of blood in a fixed facility over a period of t | $uniform$ (2950000,6600000) | $b^1_{jt}$ | Fixed facility capacity j over time t | 35000 |
| $A^2_t$ | The cost of maintaining each unit of blood in blood centers during the period t | $uniform$ (7000,10000) | $b^2_{pt}$ | The capacity of mobile facilities p in period t | 12000 |
| $A^3_t$ | The cost of maintaining each unit of blood in the hospital during the period t | $uniform$ (5000,7000) | $b^3_{ct}$ | The capacity of blood center c in period t | 200000 |
| $v_{j_1 j_2 t}$ | The cost of moving the mobile blood collection facility from location j1 to location j2 in period t | $uniform$ (25000,30000) | $b^5_{ht}$ | The capacity of hospital center h in period t | 60000 |
| $T^1_{jct}$ | The cost of transferring blood units from mobile facility j to blood center c in period t | $uniform$ (2500000,5000000) | $b^4_{it}$ | Blood donation capacity by blood donors located at location i in period t | 1000 |
| $T^2_{pct}$ | The cost of transferring blood units from a fixed facility p to a blood center c over a period of t | $uniform$ (3500000,4500000) | $cap_l$ | Most blood supply from blood group l in period t | 2000 |
| $T^3_{cht}$ | The cost of transferring blood units from blood center c to hospital h in period t | $uniform$ (3000000,4000000) | $u_c$ | The radius of coverage of mobile facilities | 230000 |
| $T^4_{cc't}$ | The cost of transferring blood units from blood center c to blood center c' in period t | $uniform$ (3000000,4500000) | $w_1$ | Fixed facility coverage radius | $uniform$ (30,60) |
| $T^5_{hh't}$ | The cost of transferring a unit of blood from hospital h to hospital h' during the period t | $uniform$ (2950000,6600000) | $w_2$ | Maximum storage capacity in the blood center c | $uniform$ (20,30) |
| $tim^3_{cht}$ | The time of transfer of blood units from blood center c to hospital h in time period t | $uniform$ (120,160) | $R^1_{cc'}$ | Distance between blood centers c and c' | $uniform$ (15,20) |
| $tim^4_{cc't}$ | The time of transfer of blood units from the blood center c to the blood center c' in time period t | $uniform$ (100,200) | $R^2_{hh'}$ | The distance between hospitals h and h' | $uniform$ (10,15) |
| $tim^5_{hh't}$ | Time of transfer of a unit of blood from hospital h to hospital h' in period t | $uniform$ (80,120) | $R^1_0$ | The radius of coverage for lateral transfers between blood centers | $uniform$ (25,35) |
| $s_h$ | Cost of shortage of blood per unit of hospital | $uniform$ (12000000,15000000) | $R^2_0$ | The radius of coverage for lateral transfers between hospitals | $uniform$ (15,20) |
| $d_{mt}$ | Demand for hospital located at point m in period t | $uniform$ (300,500) | $d_{ht}$ | The demand of h hospital in period t | $uniform$ (4500,8000) |
| $r^1_{ij}$ | The distance between the blood donor groups located at point i and the mobile blood collection facility located at location j | $uniform$ (30,50) | | | |

Regarding the number of blood transfusion centers in Tehran, there are a total of 16 fixed centers and 3 mobile teams, which are geographically located in most areas of Tehran, including active blood collection units. The distance information between the blood center and the fixed facilities is provided in the Table (7).

Table 7
Distances between the blood center and the fixed facility

| Fixed Facility | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blood Center | 8.4 | 5.2 | 7.7 | 9.5 | 10.2 | 13.0 | 14.6 | 6.7 | 6.2 | 8.3 | 7.9 | 11.3 | 9.4 | 8.7 | 7.9 | 11.2 |

The holding cost of per blood unit in a fixed facility, blood center, and hospital are also shown in Tables (8) and (9).

Table 8
Holding cost of per blood unit in the hospitals (1000 Rials)

| Hospitals | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Maintenance costs | 1150000 | 1750000 | 2010250 | 1750690 | 1640250 | 1350250 | 157620 | 1782240 |
| Hospitals | 9 | 10 | 11 | 12 | 13 | 14 | 15 | |
| Maintenance costs | 1940500 | 2010200 | 2200100 | 1500600 | 1540230 | 1450250 | 1500400 | |

Table 9
Holding cost of per blood unit in the fixed facilities (1000 Rials)

| Fixed Facility | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Maintenance costs | 1210300 | 1610200 | 1420000 | 1630800 | 1330300 | 1110000 | 1626000 | 1631600 |
| Fixed Facility | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Maintenance costs | 1420000 | 1060250 | 1630330 | 1150800 | 1100230 | 1150750 | 1250600 | 1412530 |

*- Design of experiments via Taguchi Method*

To estimate the appropriate value for the parameters of the algorithms, the Taguchi method was utilized. An experiment design is a sequence of tests in which desired changes are applied to process or system input variables to the extent that we can observe and determine the causes of changes in response. The purpose of designing experiments is to determine the variables that have the greatest effect on the response variable (y), to determine the position of the controllable variables x so that y is almost always close to the desired nominal value, to determine the position of the controllable variables x so that the variability y is small, and to determine position of controllable variables x so that the effect of uncontrollable variables is minimized. In designing experiments, the factors and their levels, selecting the response variable, and selecting the test design should be done correctly so that the results meet the needs optimally.

*- Steps to perform parameter setting*

- Designing the experiments
- Determining controllable/ uncontrollable factors, and performance measurement criteria
- Determining the levels associated with each factor
- Selecting the appropriate orthogonal arrays
- Implementing the experiments
- Analysis of experiments
- Analysis of variance to determine the most effective factors on the response variable
- Determine how each factor affects the response variable to determine the optimal levels and analyze the data using the signal-to-noise ratio
- Conclusions and Recommendations (Reliability Tests)

*- Determining controllable/ uncontrollable factors, and performance measurement criteria*

In selecting the response variable, the experimenter must ensure that the selected variable provides useful information about the process under study. In most cases, the mean or standard deviation (or both) of the measured characteristic will be the response variable. Multiple response variables are not uncommon. The efficiency of the measuring tool is also an important factor. If the measuring instrument does not work well, then the experiment will only find large effects or the experiment will have to be repeated.

*- Determining the levels associated with each factor*

The experimenter must select the factors to be changed in the test, the range of factors to be changed, and the specific levels to be considered for the test. To do so, there must be sufficient knowledge of the process. This cognition is usually a combination of practical experience and theoretical understanding. All factors that may play an important role in the experiment should be considered to avoid overemphasis on factors that may be influenced by previous experiences, especially when we are in the early stages of the experiment or when the process life is not long. When the goal is to screen for factors or process characteristics, it is usually better to consider the number of levels of the operating agent under study (often three levels are used).

Table 10
Search scope of the input parameters levels of the studied algorithms

| **parameters** | **Description** | **Domain** | **Level** | | |
|---|---|---|---|---|---|
| | | | **1** | **2** | **3** |
| nPop | Initial population size | 50-200 | 50 | 100 | 200 |
| $P_C$ | Intersection percentage | 0.6-0.8 | 0.6 | 0.7 | 0.8 |

| | | | | | |
|---|---|---|---|---|---|
| $P_m$ | Percentage of mutations | 0.1-0.3 | 0.1 | 0.2 | 0.3 |
| Iteration | The number of repetitions | 100-200 | 100 | 150 | 200 |

*- Selecting the orthogonal arrays*

In the design of experiments and development strategies, simple logic is usually used to create all possible combinations of factors with acceptable ranges in each of the relevant factors. The conventional method of reducing the number of combinations of experiments is partial factorial. Taguchi has developed a special set of blueprints for factorial experiments that cover most applications. Orthogonal arrays are part of this set of designs, and using these arrays helps us determine the minimum number of tests required for a set of factors. Some of the features of the proposed scheme for this issue are as follows:

- In this plan, only the main effects are estimated.
- To estimate the main effects, three levels of a factor with two degrees of freedom as well as one degree of freedom are needed to estimate the total average. Therefore, we need at least one degree of an experiment for each degree of freedom, so the minimum number of tests required is 9. The scheme presented here has 15 experiments, of which we have 6 more experiments.
- Main effects estimates can be used to predict the response of each combination of factor levels. An optimal design is one in which the variance of the prediction error is the same as the factorial design.

Table 11
Orthogonal Arrays and NOS Values

| Experiment number | nPop | $P_c$ | $P_m$ | Iteration | NSGA-II |
|---|---|---|---|---|---|
| | | | | | NOS |
| 1 | 2 | 3 | 2 | 1 | 38 |
| 2 | 1 | 1 | 1 | 1 | 51 |
| 3 | 2 | 1 | 2 | 2 | 47 |
| 4 | 1 | 2 | 2 | 2 | 42 |
| 5 | 3 | 1 | 3 | 2 | 41 |
| 6 | 1 | 2 | 2 | 2 | 39 |
| 7 | 1 | 3 | 3 | 3 | 38 |
| 8 | 1 | 3 | 3 | 3 | 43 |
| 9 | 3 | 3 | 3 | 3 | 36 |
| 10 | 2 | 1 | 2 | 1 | 35 |
| 11 | 2 | 3 | 3 | 1 | 43 |
| 12 | 2 | 1 | 2 | 1 | 41 |
| 13 | 2 | 1 | 1 | 2 | 46 |
| 14 | 3 | 1 | 3 | 2 | 42 |
| 15 | 3 | 1 | 3 | 3 | 44 |

*- Specifying the optimal levels for the parameters*

The purpose of these experiments here is to find a combination of levels of control factors such that for the quantitative variable of the objective function the mean value is as large as possible and the standard deviation for the above response variable is minimized. This is known as optimizing the combination of levels of control agents. To achieve this, the performance criterion proposed by Taguchi, the S/N ratio, is considered as the response variable. The response variable must be as large as possible, so the associated variable corresponds to the "bigger is better" state. According to this, the S/N ratio for the above variable will be as follows.

Fig 4 shows how the values of the S/N index change at different levels of the algorithm. Levels, where the S/N index has reached its maximum, can be selected as the optimal levels.

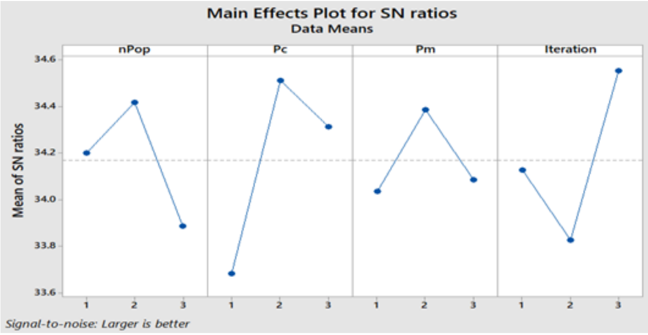


Fig. 4. S/N index values at different levels of NSGA-II algorithm parameters

Table 12
Ideal Factor Levels for Proposed Algorithms

| Algorithm | parameters | Description | Optimal level |
|---|---|---|---|
| NSGA-II | nPop | Initial population size | 150 |
| | $P_C$ | Intersection percentage | 0.7 |
| | $P_m$ | Percentage of mutations | 0.2 |
| | Iteration | The number of repetitions | 200 |

Due to a large number of effective parameters in the MOPSO algorithm, determining the values of the parameters using the Taguchi method is very difficult and time-consuming, so the error and trial method has been used by the researcher to obtain the parameters of this algorithm. Table (13) illustrates these parameters and their values.

Table 13
Parameters used in MOPSO algorithm

| Parameters | Amounts |
|---|---|
| Maximum number of repetitions | MaxIt = 150 |
| Population size | nPop = 80 |
| Tank size | nRep = 60 |
| Inertia weight | w = 0.04 |
| Inertia weight reduction rate | wdamp = 0.98 |
| Personal learning coefficient | c1 = 1.2 |
| Global learning coefficient | c2 = 2 |
| Number of nodes | nGrid = 6 |
| Inflation | alpha = 0.15 |
| The pressure of leader selection | beta = 2 |
| The pressure of Select Delete | gamma = 2 |
| Mutation rate | mu = 0.45 |

Table 14
Calculated values for the cost objective function

| Components of the objective function | NSGA-II | MOPSO |
|---|---|---|
| The cost of constructing a fixed site | 32565000 | 32565000 |
| The cost of moving a mobile blood collection facility | 2632154 | 2632514 |
| The cost of transferring blood units from mobile facilities to blood centers | 4610462 | 1810450 |
| The cost of transferring blood units from fixed facilities to blood centers | 8643520 | ` |
| The cost of transferring blood units from blood centers to hospitals | 6352536 | 5217352 |
| Cost of transfer of blood units between blood centers (lateral transfer between blood centers) | 856325 | 987862 |
| Cost of blood unit transfer between hospitals (lateral transfer between hospitals) | 752632 | 864925 |
| The cost of maintaining each unit of blood in a fixed facility | 2730870 | 1431256 |
| The cost of maintaining each unit of blood in blood centers | 241563 | 251630 |
| The cost of maintaining each unit of blood in hospitals | 125634 | 175862 |
| Deficit cost | 251974 | 3341659 |
| The cost of corruption | 4643356 | 9532164 |
| total cost | 64136026 | 65353719 |

According to the values in Table (14), for the cost objective function and each of its components separately, it can be seen that the values obtained using the NSGA-II metaheuristic algorithm were less than the MOPSO algorithm. In the validation of the algorithms, this result was determined using numerical examples. Thus, 51% of the costs are related to the cost of construction of fixed facilities, 4% of the cost of moving mobile blood collection facilities, 7% of the cost of transferring blood units from mobile facilities to blood centers, 13% of the cost of transferring blood units from fixed facilities to blood centers, N, 10% cost of transferring blood units from blood centers to hospitals, 1% cost of transferring blood units between blood centers (lateral transfer between blood centers), 4% cost of transferring blood units between hospitals (lateral transfer between hospitals) 0.3% of the cost of maintaining each unit of blood in a fixed facility, 0.1% of the cost of maintaining each unit of blood in blood centers, 0.3% of the cost of maintaining each unit of blood in hospitals, 0.03 of the cost of shortage and 7% is the cost of corruption (expiration).

*Resulting Values for the time objective function*

After solving the model using metaheuristic algorithms, the value of the objective function over time based on each of its components is presented in the Table (15). Note that the components of the objective function over time are: (1) the time for transferring blood units from blood centers to hospitals, (2) the time for transferring blood units between blood centers (lateral transfer between blood centers), and (3) the time for transferring blood units between hospitals (lateral transfer between hospitals).

Table 15
Values of the time objective function

| Components of the objective function | NSGA-II | MOPSO |
|---|---|---|
| Time to transfer blood units from blood centers to hospitals (minutes) | 24321 | 26542 |
| Time of transfer of blood units between blood centers (lateral transfer between blood centers) | 14532 | 15623 |
| The transmission time of blood units between hospitals (lateral transfer between hospitals) | 8695 | 9562 |
| Total time | 47548 | 51727 |

Table 16
Amounts of expired products, shortage of hospitals and the number of the delivered products in Vesal Shirazi blood center

| Demand Centers (Hospitals) | Blood product | Amount | Shortage | Expired |
|---|---|---|---|---|
| H1 | Product 1 | 356 | 3 | 8 |
| | Product 2 | 428 | 0 | 3 |
| H2 | Product 1 | 369 | 0 | 6 |
| | Product 2 | 268 | 2 | 2 |
| H3 | Product 1 | 406 | 1 | 1 |
| | Product 2 | 323 | 0 | 3 |
| H4 | Product 1 | 290 | 0 | 6 |
| | Product 2 | 96 | 0 | 2 |
| H5 | Product 1 | 194 | 2 | 5 |
| | Product 2 | 291 | 1 | 4 |
| H6 | Product 1 | 367 | 5 | 9 |
| | Product 2 | 442 | 0 | 5 |
| H7 | Product 1 | 239 | 1 | 3 |
| | Product 2 | 328 | 0 | 2 |
| H8 | Product 1 | 621 | 0 | 1 |
| | Product 2 | 406 | 2 | 6 |
| H9 | Product 1 | 68 | 0 | 2 |
| | Product 2 | 89 | 0 | 4 |
| H10 | Product 1 | 163 | 6 | 1 |
| | Product 2 | 356 | 0 | 2 |
| H11 | Product 1 | 571 | 0 | 21 |
| | Product 2 | 268 | 0 | 2 |
| H12 | Product 1 | 301 | 2 | 1 |
| | Product 2 | 412 | 0 | 16 |
| H13 | Product 1 | 330 | 0 | 3 |
| | Product 2 | 234 | 0 | 1 |
| H14 | Product 1 | 460 | 0 | 2 |
| | Product 2 | 261 | 1 | 2 |
| H15 | Product 1 | 238 | 0 | 5 |
| | Product 2 | 209 | 0 | 4 |
| Total amount | | 9384 | 26 | 132 |

Given the multi-objective nature of the model used in the research, the obtained solutions from each algorithm are represented as a Pareto set. This means that since we have three objective functions and these objectives are conflicting with each other (e.g., to achieve a shorter delivery time, a higher delivery cost must be considered, etc.), it is not possible to reach an optimal solution that simultaneously optimizes all three objective functions. Therefore, we have a set of solutions available that show a desirable level of achievement for each objective. The following figures and tables illustrate the subset of the Pareto solution set based on the solutions obtained by the algorithms.

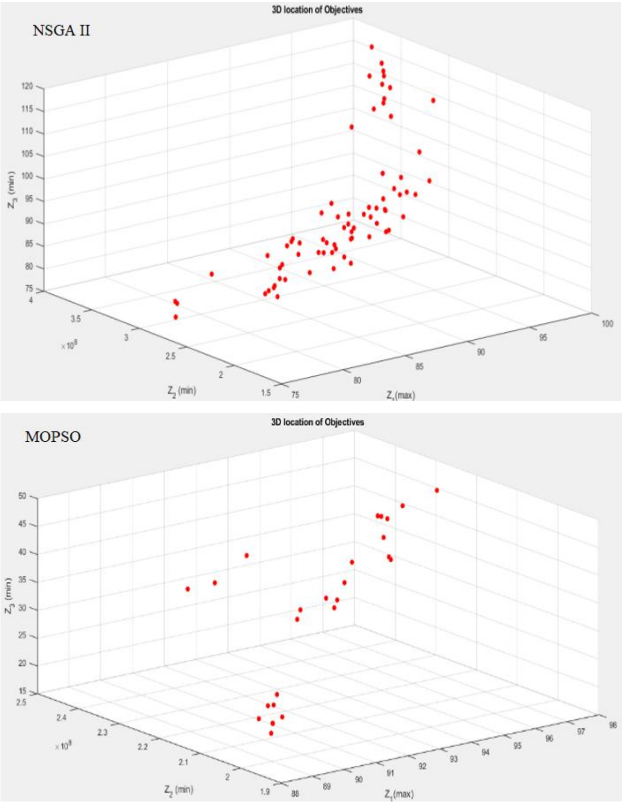


Fig. 5. Pareto solution of the NSGA-II (Left) and MOPSO (Right) algorithms

Table 17
Pareto answers of the objective functions

| NSGA-II | | | MOPSO | | |
|---|---|---|---|---|---|
| **Z1** | **Z2** | **Z3** | **Z1** | **Z2** | **Z3** |
| 65235620 | 48563 | 28 | 67586943 | 50362 | 36 |
| 64256321 | 46932 | 29 | 69325648 | 52461 | 35 |
| 66325154 | 47532 | 32 | 66326598 | 53021 | 32 |
| 65326981 | 49326 | 27 | 67958634 | 52369 | 31 |

## 5. Conclusions

Blood management is an issue that has raised special concerns for humanity. Even though many technological advances have been made to replace blood products, the need for donor blood and its derivatives remains forever. Blood is not an ordinary commodity. Blood donation by the donor is completely unusual and the demand for a blood product is at its best probable. Matching supply and demand in the blood supply chain is not without problems. Blood products are also perishable, which complicates the issue at hand. One must bear in mind that since anemia can lead to an increase in mortality rate, it can have profound negative effects and impose costs on society. The reasons mentioned above are just a few of the many reasons that encourage any researcher to research blood supply and in particular the blood supply chain. In this research, a nonlinear mixed-integer programming model for blood supply chain design is presented. In this research, the queue system was used for modeling.

The intended supply chain is a four-tier supply chain consisting of blood donation centers, blood laboratories, blood bank centers, and demand centers. The objectives of the proposed model are: 1) Determining the location of donation centers and blood bank centers, 2) Determining the number of transfer products between each point of the supply chain. In this study, most of the complexities of the problem are considered. Complications such as blood loss in laboratories, analysis of blood products in the laboratory, multi-product nature of the problem, transfer of blood products between demand points, etc.

Since in the real world, the model parameters are usually indefinite and their exact amount is not known; the parameters of the uncertain model are also considered. The model of this research is solved for problems of small size using precise methods; but because the problem can not be solved with larger methods in larger sizes, the meta-heuristic algorithm of genetic algorithm and multi-purpose bird movement was used. The model of this study was a three-objective model that included minimizing the total costs, minimizing the total time of blood transfusion, and minimizing the maximum unmet demand of hospitals in each period.

The proposed supply chain model consisted of four products: whole blood, plasma, platelets, and red blood cells. In this model, complex problems of blood group matching are considered. In this case, when there is not enough of one blood type, blood groups that can replace that blood type are utilized. Sensitivity analysis of the sensitive parameters of the problem showed that increasing the amount of blood loss in laboratories increases the value of the cost objective function. Increasing the level of uncertainty increases both the cost and time functions. Reducing the blood donation rate increases the cost by creating a deficit in the value chain function. So the value of the cost function is directly related to the value of the penalty coefficient. As demand increases, the cost objective function shows an increasing trend.

The following suggestions may be considered for future studies:

- Considering the possibility of breakdowns and downtime of supply chain centers,
- Considering routing issues and combining them with allocation and location issues,
- Development of other methods for optimization problems under large size uncertainties which can contribute to research value,
- Considering inventory control issues in the blood supply chain, especially in blood banks, which can make the model more comprehensive,

- Combining discrete and continuous location problems to formulate the model,
- Providing a dynamic model in which mobile donation centers such as blood collection centers can be considered,
- Considering the design of blood supply chains in crises can be a big step in this field of research in terms of real-world situations

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